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The effects of forsterite film on total loss of grain-oriented 3% silicon iron

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Two types of mill glass, one of which is conventional and the other is characterized by its irregular surface morphology and stronger tension, were prepared on the surface of high permeability 3%Si-Fe sheets in order to clarify the effects of the mill glass on core loss and domain structure. The results are twofold. Firstly, the mill glass of the latter type was, by itself, found to reduce the total loss in the induction range of 1.7 T. Secondly, considerable change in magnetization, characterized by its heavily constricted curve occurred, and corresponding change in the domain structure was observed.

INTRODUCTION

The core loss of grain-oriented 3%Si-Fe is known to be influenced by many factors. Orientation dependence of domain wall spacing and losses was studied by Shilling *et al.*[1] and Nozawa *et al.*[2] The effect of forsterite film and subsequent stress coatings was studied by Yamamoto and Nozawa who concluded that the tensile stress induced by the forsterite film reduced the total loss.[3] Littmann has shown, however, that the reduction by the film takes place only when induction range was about 1.5 T or less,while further stress coating did reduce the core loss regardless of the induction range.[4] Swift *et al.* have shown that smooth surfaces produced significantly lower loss than rough surfaces.[5] By using SEM, Irie and Fukuda revealed the effect of coatings on the refinement of 180° domain wall spacing and removal of surface closure domains.[6] Studies on the effect of the forsterite film and stress coating[7–12] can be summarized as follows: (1) 180° domain wall spacing is reduced by the forsterite, provided the grain has some degree of misorientation. (2) A rough surface with subsurface oxide particles causes pinning of 180° domain wall motion and thereby increases the total loss. On the other hand, forsterite is formed through the solid state reaction expressed as $2MgO + SiO_2 = Mg_2SiO_4$, and SiO_2 is formed by high temperature oxidation during a decarburizing anneal. Some basic studies have been performed in these fields.[13–16] Two distinctive types of mill glass were prepared and their effects on core loss and domain structures were investigated. The fabrication method of the mill glasses will be published elsewhere since it is beyond the scope of this report.[17]

EXPERIMENT

Nominal 0.30 mm gauge, final annealed, high permeability 3%Si-Fe sheets were prepared at our laboratory and sheared into strips of 6×30 cm followed by stress relief annealing. Stress induced by the glass was measured using a deflection method.[18] The mill glass (forsterite film and subsurface oxide particles) was removed by chemical polishing using a solution of H_2O_2 and fluoric acid. Permeability and core loss before and after the removal of the mill glass were measured with a single sheet tester.[19] Magnetization curves were measured using a dc fluxmeter. Static domain structure was observed with Bitter technique.[20] Scanning electron microscopy (JSEM-200) was also employed for domain observation.[21,22] Orientation of each grain was determined by the Laue x-ray back reflection technique.

RESULTS AND DISCUSSION

Two groups of 3%Si-Fe sheets were prepared, which will be termed group A and B hereafter. Table I gives the main characteristics of these two samples. Samples in group A have nearly the same properties as commercially produced high permeability material called HI-B.[23] Cross-sectional views of their mill glasses are shown in Fig. 1. An irregular surface morphology with subsurface oxide particles is clearly seen for sample B. Dependence of core loss at 1.7 T on permeability of the material (expressed as B_8 meaning induction at $H = 800$ A/m) is shown in Fig. 2. The core loss of samples B is lower than that of samples A for a B_8 at 1.93 T and higher. The differences of the core loss before and after the removal of the mill glass were plotted in Fig. 3. All A samples exhibited a decrease in loss with mill glass removal,the difference being smaller with increasing permeability. Several of the B samples with higher permeability exhibited no change or an increase in loss with mill glass removal.

In Fig. 4 are shown the static domain structures of the mill glass samples and the grain configurations with their misorientation angles. It can be noticed that 180° wall spacings are uniformly refined in sample B despite its large grain size. dc magnetization curves were measured before and after the removal of the mill glass. As seen in Fig. 5(c), the *B*-

TABLE I. Comparison of the samples A and B. (*1) induction of samples with mill glass. (*2) sample thickness is 0.28 (mm). (*3) Hc; dc coercive force (A/m), Br; remanence (T), *b* and *a* indicate before and after the mill glass removal, respectively.

Sample group	Induction at 800 Å/m(*1)	Average grain diameter	Stress induced by mill glass (*2)	(*3) *Hc,b*	*Hc,a*	*Br,b*	*Br,a*
A	1.90–1.95 (T)	0.8 (cm)	3.4 (MPa)	4.6	5.4	0.96	1.32
B	1.90–1.95 (T)	1.5 (cm)	5.9 (MPa)	4.0	5.9	0.42	1.36

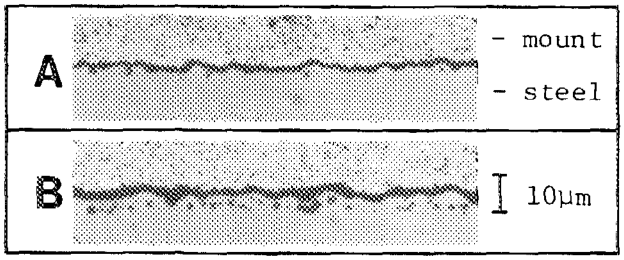

FIG. 1. Cross sectional views of the mill glass A and B.

H curve for sample B is distinctively constricted and this constriction disappears after the removal of the glass. Typical values of the dc coercive force and the remanence of those samples were tabulated in Table I. No significant difference in the area of the loop, corresponding to the dc hysteresis loss, of the mill glass samples A and B was confirmed.

Domain structures along the dc magnetization curves were observed by SEM for the mill glass samples. Figs. 6(a) and 6(f) correspond to the demagnetized state of the samples A and B, respectively, 6(c) and 6(h) to the state when $H = 800$ A/m, 6(e) and 6(j) to $H = 0$ A/m, i.e., the remanence, and the others to the intermediate magnetization. From this observation we found that the magnetization processes of samples A and B are somewhat different. At the initial increase in magnetic field, the 180° domain walls of sample B move sluggishly resulting in low initial permeability. As the field increases the narrow domain turns into a row of lancets. When this process starts, the lancets reduce their size fairly swiftly resulting in a high tangent in the *B-H* curve. As the field decreases, the aligned lancets are easily turned into narrow 180° domains in sample B, while in A many rows of lancets did not coalesce until some reverse field was applied, giving rise to the difference in their remanence values. It is interesting to note that the width of newly created 180° domain in sample B is narrower than that of demagnetized state, while that of sample A has almost equal size. As a reverse field is applied, 180° walls in sample B move sluggishly until lancets appear so that the coercive force is nearly same as that of sample A.

Several results obtained for sample B are in discord with previous observations. To our knowledge, improvement of the core loss by the mill glass per se in the induction range of 1.7 T or more has not been reported before. The reduction in total loss can be attributed to the lowering in eddy current loss, on which it is known that 180° wall spacing and mobility of the domain wall have significant influence.[24] The refinement of 180° wall spacing was found uniform despite its large grain size. The way of the magnetization as a whole is most eloquently described by its strongly constricted *B-H* loop. While the 180° wall motion was observed to be dragged by the rough surface, the nucleation and coalescence of lancets into reverse domains occur easily, resulting in a very low remanence value. This may be related to the unexpectedly low core loss brought by the mill glass of sample B since it is lancet motion that is dominant in the magnetization process when induction is high.[25] The favorable effects of the mill glass came probably from a combination of strong tensile stress and an irregular surface structure that presumably gives rise to an increase in magnetostatic energy, which may create unstable reverse domain nuclei.

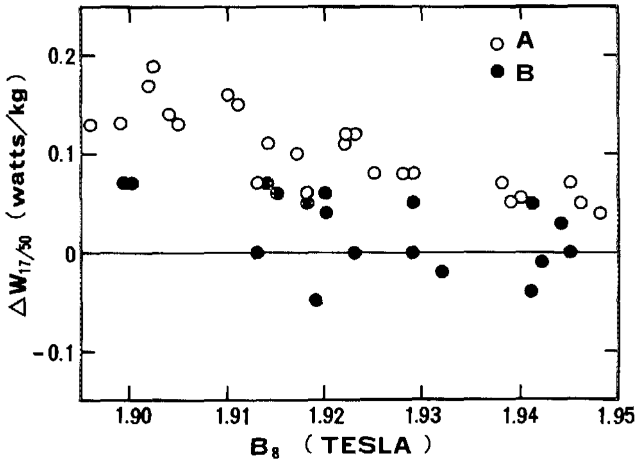

FIG. 3. Relationship between B_8 of the specimens and the differences in total loss before and after the removal of the forsterite film. $\Delta W = W_{17/50}$ (with forsterite film) $- W_{17/50}$ (chemically polished).

CONCLUSIONS

(1) A certain kind of mill glass per se is effective in lowering core loss in the induction range of 1.7 T. Its improve-

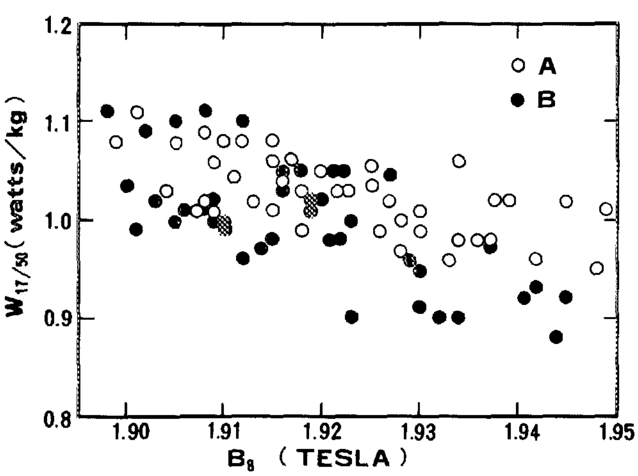

FIG. 2. Dependence of total loss at 1.7 T, 50 Hz on B_8 of the specimens.

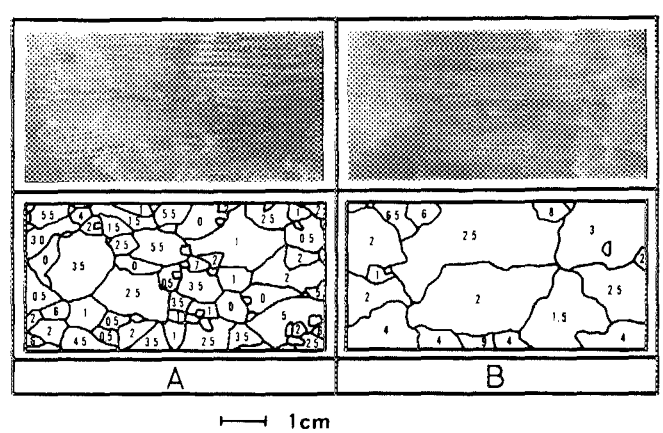

FIG. 4. Static domain structures of the mill glass specimens and their grain configuration. Numbers indicate misorientation angles of each grain.

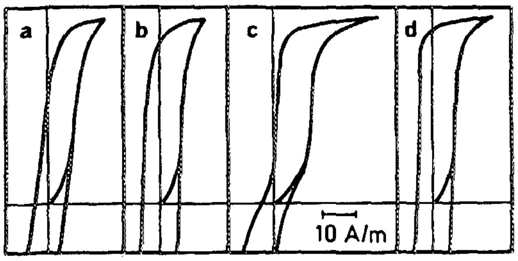

FIG. 5. dc hysteresis curves with peak induction of 1.5 T. (a) sample A with mill glass; (b) sample A chemically polished; (c) sample B with mill glass; (d) sample B chemically polished.

ment becomes larger as permeability of the material increases.

(2) A strongly constricted magnetization curve was observed for the sample above. Although 180° domain wall motion was observed to be dragged, lancet nucleation and coalescence are found to take place easily.

(3) The desired character of such mill glass seems to be a combination of appropriate roughness, which presumably results in an increase in magnetostatic energy, and strong tensile stress.

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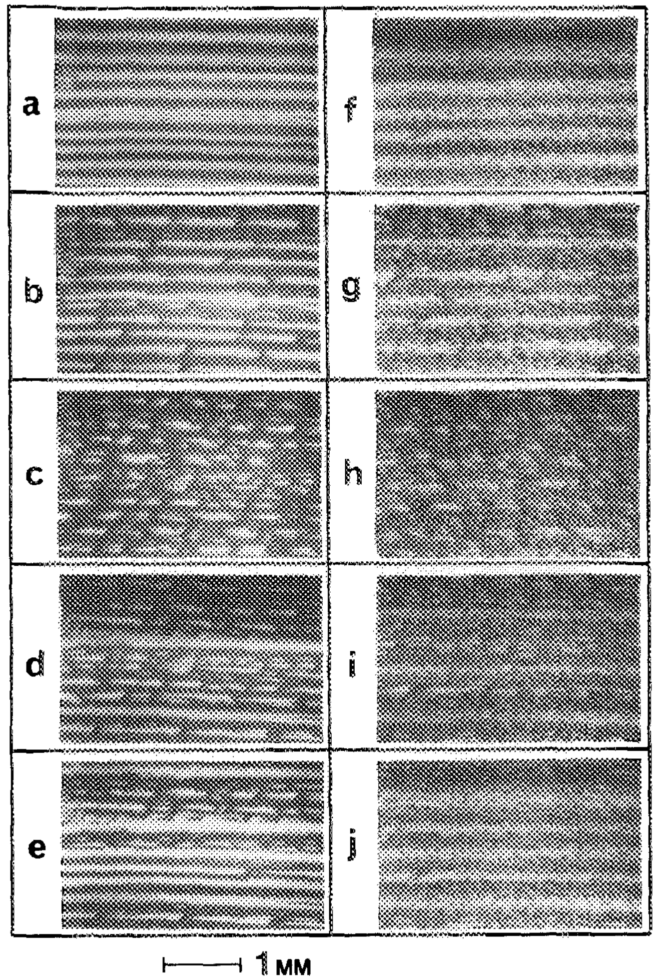

FIG. 6. Domain structure along the dc hysteresis curve. (a)–(e) are for sample A, (f)–(j) for sample B. Misorientation angles are 3.0° and 3.5°, respectively.

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